

Day of Launch Profile Selection for Pad Abort Guidance

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A day of launch selection approach that involves choosing from an array of pitch profiles of varying loft was analyzed with the purpose of reducing the risk of a land landing failure during a pad abort. It was determined that selecting from three pitch profiles can reduce the number of waterline abort performance requirement failures approximately in half without compromising other performance metrics.

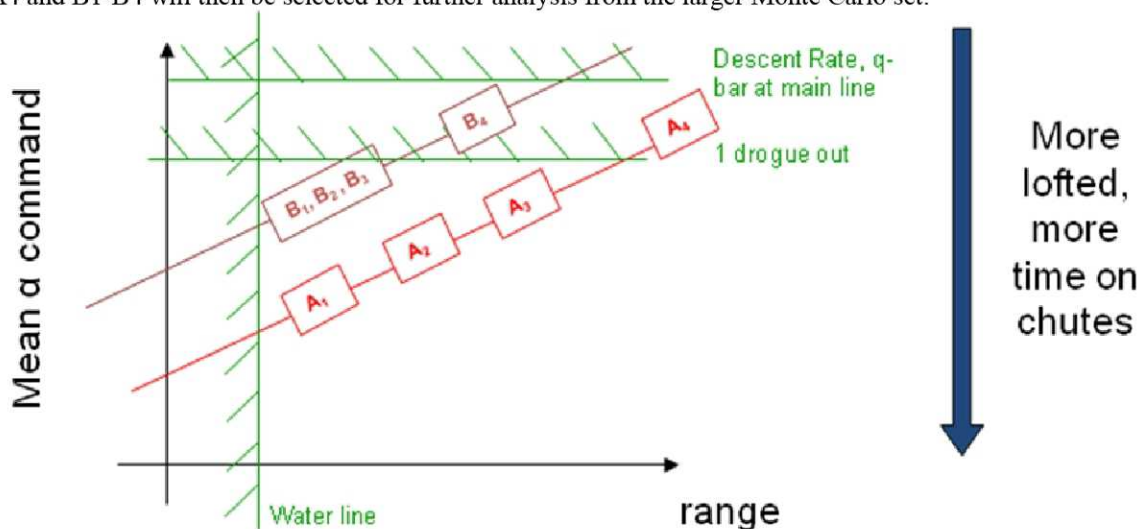
I. Introduction

THE pad abort GN&C system is designed to “place the LAV on a trajectory that provides the shortest distance to the shoreline from the launch pad in order to achieve a water landing”.¹ The rationale behind this trajectory profile is that the nominal vehicle is only designed to withstand a water landing, so the inability to achieve this condition is considered an abort failure. However, a pitch profile cannot be designed solely to reach the water; if the angle of attack is too large during the abort motor firing, the depressed trajectory and reduced timeline can increase the risk of a main chute inflation failure which is arguably more undesirable than a land landing. Because of this tradeoff, a significant driver in ensuring a successful pad abort relates directly to the particular wind of the day.

It is this fact that prompts the design of wind-tailored pitch maneuver profiles. In general, there appears to be two types of wind days: those that provide tailwinds and aid in pushing the vehicle towards the water and those that provide headwinds and impede this motion. Thus this trade study is designed to analyze how effective it would be to tailor the pad abort pitch profile to these two types of winds along with a third compromise profile designed for mild winds. The idea is to reduce the size of or replace the need for wind placards, and the degree to which this is effective will justify the use of this type of I-load.

II. Methodology

The pitch profiles for this analysis were designed based off two categories of winds. Category A focused on dealing with tailwinds, generally favorable for a water landing. Category B focused on headwinds or those generally unfavorable for a water landing. For each category a representative wind was selected so that the pitch profile tables were the only independent variables. These pitch profile tables were varied randomly through the use of the Monte Carlo capability in order to generate data equivalent to the cartoon shown in Figure 1 below. Pitch profiles such as A1-A4 and B1-B4 will then be selected for further analysis from the larger Monte Carlo set:



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Figure 1. Methodology for establishing pitch profiles based on head and tailwinds

The green constraint lines shown in Figure 1 outline the limits for a successful pad abort due to either waterline (where the angle of attack command is smaller) or descent rate failure (where the angle of attack is larger). The second horizontal line (with 1 drogue out) is a tighter constraint that protects for a failed drogue chute that naturally needs less average angle of attack to cause a descent rate exceedance failure. The selected pitch profiles were then fixed individually for full pad abort Monte Carlos to see how dispersions impacted the results. Based on an analysis of the resulting failures a categorization process was set up to select profiles for a given day in a number of different scenarios. The way in which this categorization was completed served as the basis for comparison for the trade study. In addition, wind placards were assessed.

III. Results and Discussion

A. Designing Sets of Pitch Profiles for Category A

The methodology in section II is applied to trajectories in Category A using the same average February wind. The range was recorded at touchdown and the average angle of attack was calculated solely from the initial pitch over maneuver portion of the trajectory, around the time of the abort motor firing. Due to the favorable out to sea direction of the wind it was necessary to loft the wind with a negative angle of attack in order to get water failures. The increased loft of these trajectories prevented the vehicle for progressing directly to the water. As a result, the calculated range is not in the direction perpendicular to the coastline and therefore the first water failure occurs at a range greater than the shortest possible range. (The shortest range to the coastline is approximately 1060 m.)

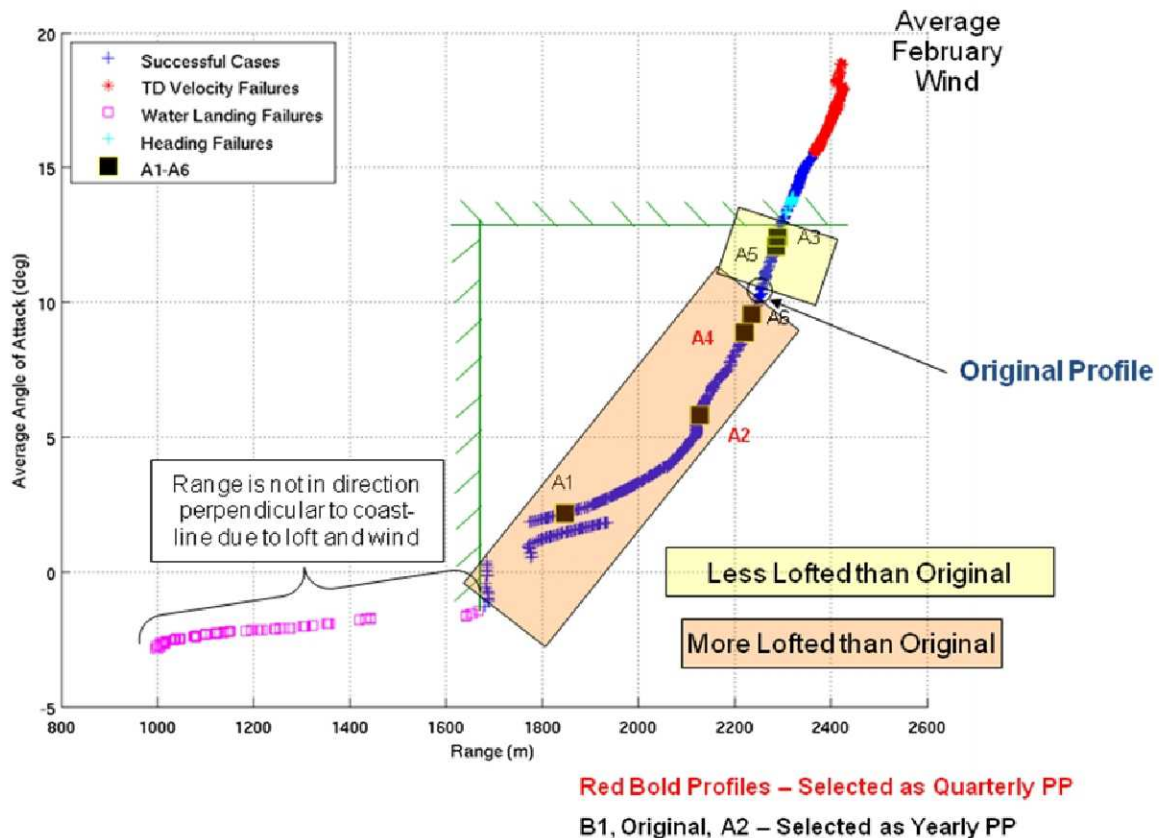


Figure 2. Category A (favorable headwinds) pitch profile design space

From this data, a number of pitch profiles were evaluated as possible candidates for days with tailwinds. Some of these trajectories were less lofted than the original and still met the success criteria, however, more lofted trajectories are the focus of this regime since all other parameters are generally aided by loft, as shown by the following plot:

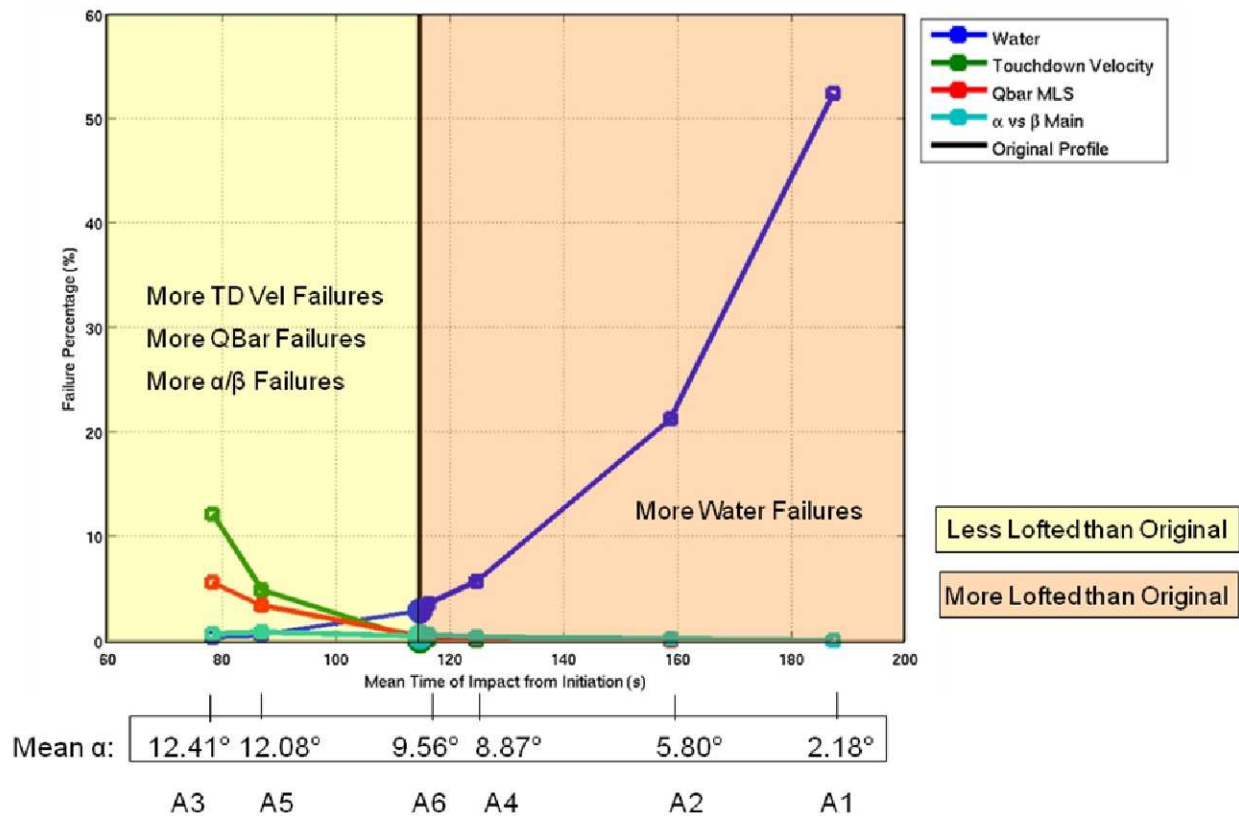


Figure 3. Degree of loft trade space; Failure percentage vs. trajectory time

The figure above demonstrates that in a general sense (for all wind cases), a more lofted profile is more conducive to a successful pad abort in almost all of the other failure metrics. Thus, for a tailwind, where the vehicle is already being pushed out into the ocean, a lofted trajectory is logical.

Trajectories A2 and A4 were selected for further analysis with A2 being the general all year large tailwind profile with an average angle of attack of 5.8 degrees, approximately 4 degrees less than the original profile.

B. Designing Sets of Pitch Profiles for Category B

The following figure shows how the section II methodology is applied to an October wind, which serves as a representative Category B headwind. Once again the range was calculated at touchdown and the average angle of attack was based on the initial pitch over maneuver. With a headwind, it takes much less loft than a tailwind to produce a water line failure. Therefore, the first range where this occurs is approximately equal to the shortest range to the coastline (1060 m).

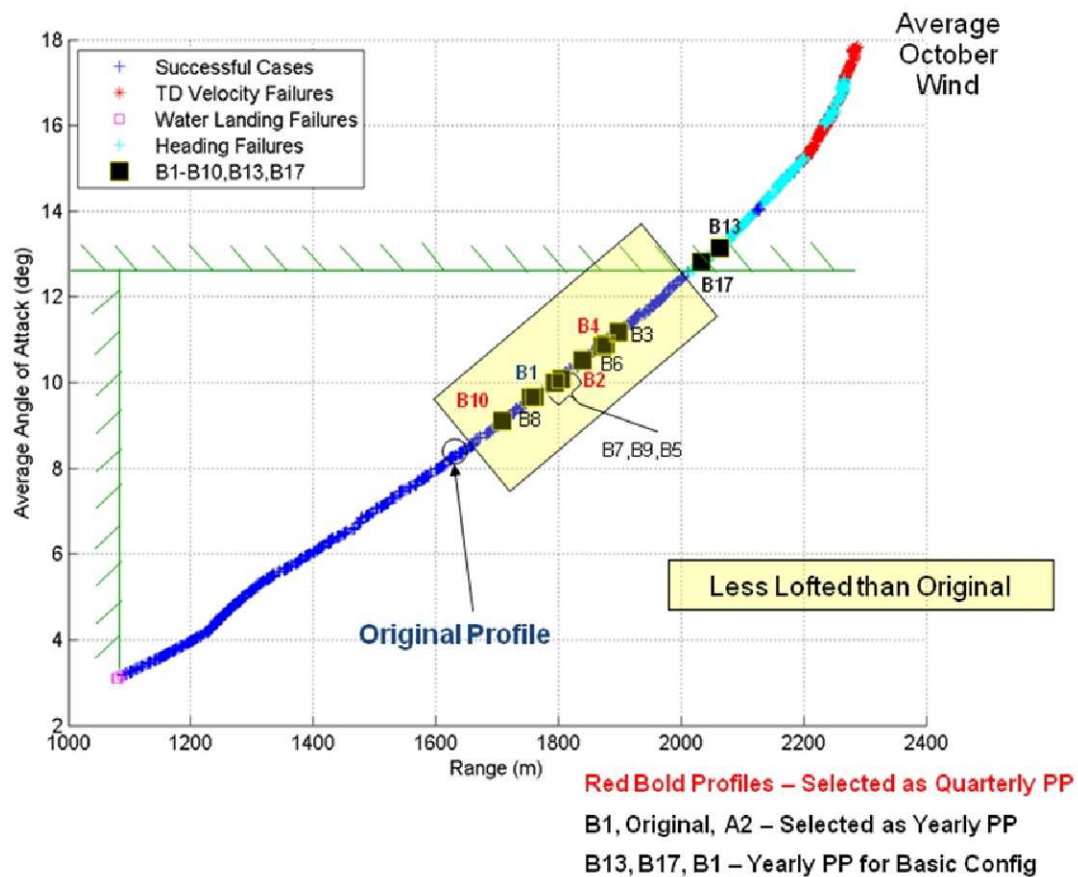


Figure 4. Category B (unfavorable tailwinds) pitch profile design space

While more lofted trajectories exist within the acceptable bounds on the above plot (to the left of the original profile), only less lofted profiles were evaluated. As evidenced by the tighter bounds, and the negative trending associated with less loft, Category B winds are decidedly more sensitive to varying pitch maneuver sequences than Category A winds.

The B1 pitch profile ended up being selected for headwinds year-round, while B4, B2 and B10 were also used depending on the quarter. B1 has an average angle of attack of about 9.6° which is slightly more than 1° larger than the original profile. As an example of how quarterly profile design is helpful, B4 ($\alpha=11^\circ$) is used for the largest headwinds in October, but should not be applied too liberally as the de-lofted profile is very susceptible to touchdown velocity failures.

C. Wind Categorization by Season and Year

The following table shows the profiles selected for the different types of wind broken down by time of year against a full year evaluation. The quarterly selections are shown in the first four rows and the yearly profiles are in the final row. The selection/categorization is based on mean wind values. The mean winds are placed in the different buckets (headwind, tailwind and compromise) by analyzing their value compared to a multiplier on the standard deviation from 0 (neutral wind). The mean wind values are calculated from winds that are positive blowing towards the North-East. In other words, tailwinds produce positive wind values, while headwinds produce negative winds. Each case average value is based on the latter half of the entire trajectory. The shallowest pitch profile used (B4) produced too many touchdown velocity failures so this limit was expanded to more than 2 standard deviations. The 4th quarter winds are generally the most problematic. The same profiles performed equally well for ISS and Lunar mass configurations, while the lighter Basic configuration could take advantage of shallower profiles:

Table 1. Pitch Profile Selections Based on Mean NE Winds

Category	Wind	Lower Limit	Upper Limit	Pitch Profile (ISS/Lunar)	Pitch Profile (Basic)
1: Jan, Feb, Mar	Headwind		-1 standard deviation	B2	
	Tailwind	0		A2	
	Compromise	-1 std	0	B10	
2: Apr, May, Jun	Headwind		-1 std	B2	
	Tailwind	0		A2	
	Compromise	-1 std	0	A4	
3: Jul, Aug, Sep	Headwind		-1 std	B2	
	Tailwind	0		A2	
	Compromise	-1 std	0	A4	
4: Oct, Nov, Dec	Headwind		-2 std	B4	
	Tailwind	0		A4	
	Compromise	-2 std	0	B10	
All Year	Headwind		-1.5 std	B1	B13
	Tailwind	0.5 std		A2	B1
	Compromise	-1.5 std	0.5 std	Original	B17

The following series of scatter plots demonstrate the profile selection process for the different proposed configurations. The plots focus on the 4th quarter winds as these months produce the largest headwinds and are therefore the most difficult to categorize for optimum success. The first plot shows the shallow profile B4 applied to 2000 cases from this quarter:

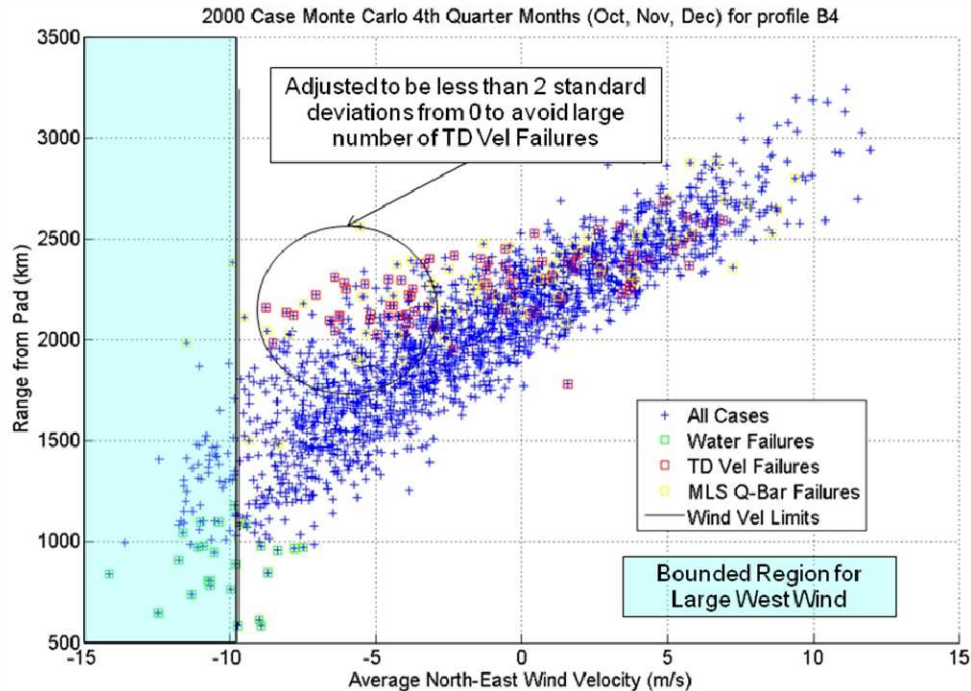


Figure 5. Headwind tailored profile assessment

There exists a general linear trend between average wind velocity and range from the pad, but this is clearly not a perfect trend. Many cases in spite of the profile and seeming large headwind tend to gather more range than others. Many of these cases, as shown by the circle, exceed the touchdown velocity metric, which is considered to be a more severe failure than hitting the ground. Thus, this particular profile could only be applied to wind cases larger than 2 standard deviations from 0. The shallow profile is really tailored for those strong October winds which without an 11° angle of attack will never reach the water.

With the headwinds being limited to 2 standard deviations are lower from 0, the compromise winds, from 2 standard deviations to 0, could actually be labeled as small to medium headwinds. This means that generally speaking, with even a small tailwind (the final category), the profile can be lofted. For the compromise winds, a slightly shallower than original profile was selected B10:

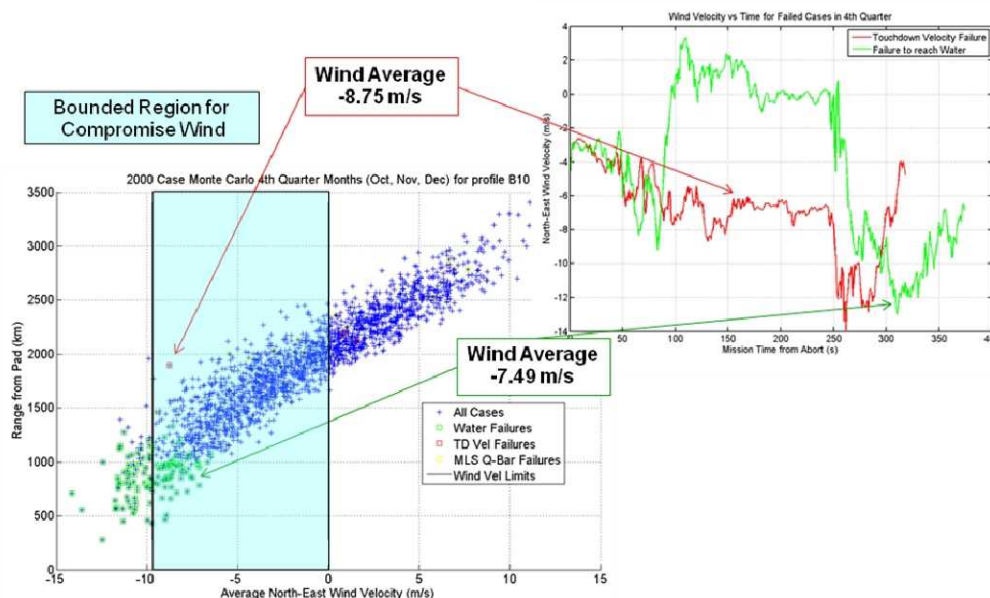


Figure 6. Compromise wind tailored profile trade

The two cases highlighted here show how other Monte Carlo dispersions impact the outcome. In fact, the case that was a touchdown failure appears to be a larger headwind than the case that doesn't reach the water. This is the essence of the compromise. If wind was the only factor we could much more easily devise average profiles (not day-of-launch tailored) that could make almost any wind day a successful one.

The final category of winds is the tailwinds. Here, all of the winds have positive values and a lofted profile is successful in getting all of these cases to the water:

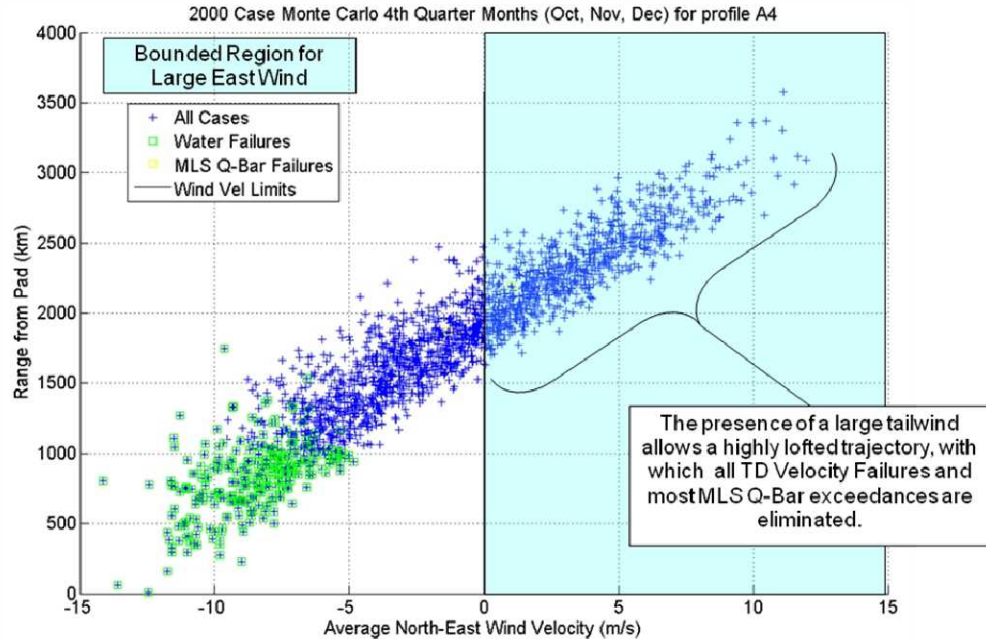


Figure 7. Tailwind tailored profile trade

While the plot above demonstrates that there are definitely more headwinds than tailwinds in the October-December quarter, there still can be some significant tailwinds. Thus the use of quarterly designed winds loses its appeal when it is shown that every quarter and every month exhibits a large variation of winds, as exhibited by the following plot comparing October (traditionally viewed as the headwind month) to February (traditionally viewed as the tailwind month):

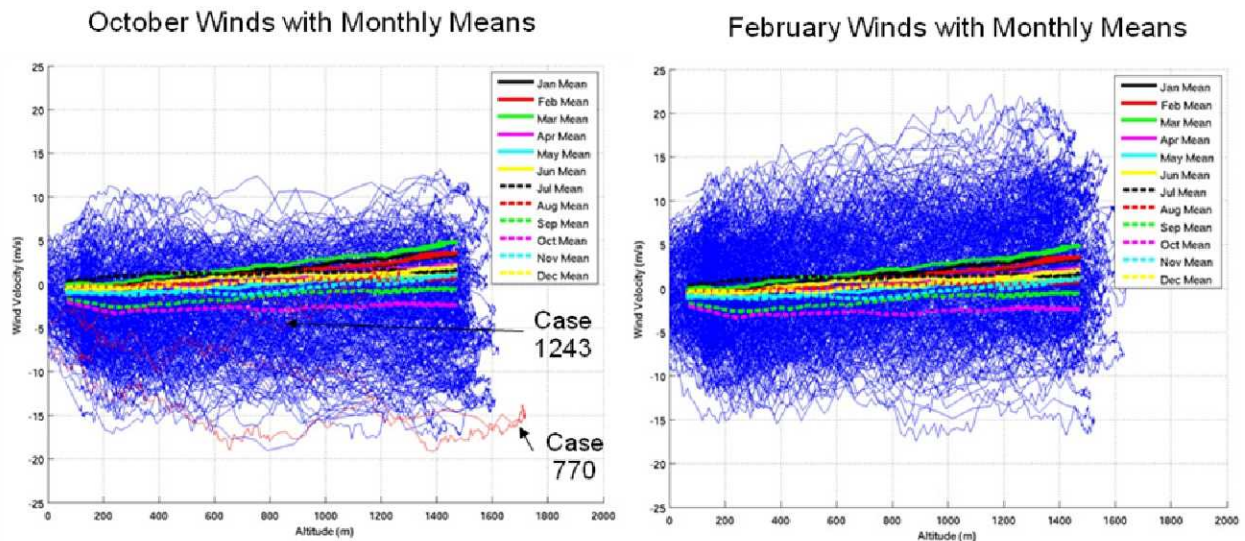


Figure 8. Comparing October and February winds with monthly means

D. Water Failure Reduction with Profile Selection

Once the selection analysis was complete and the profiles selected as in Table 1 above, the effect of the new profiles can be compared. The following bar chart shows the change in the target metrics based on the profile selections for a 2000 case Monte Carlo with cases randomly selected throughout an entire year:

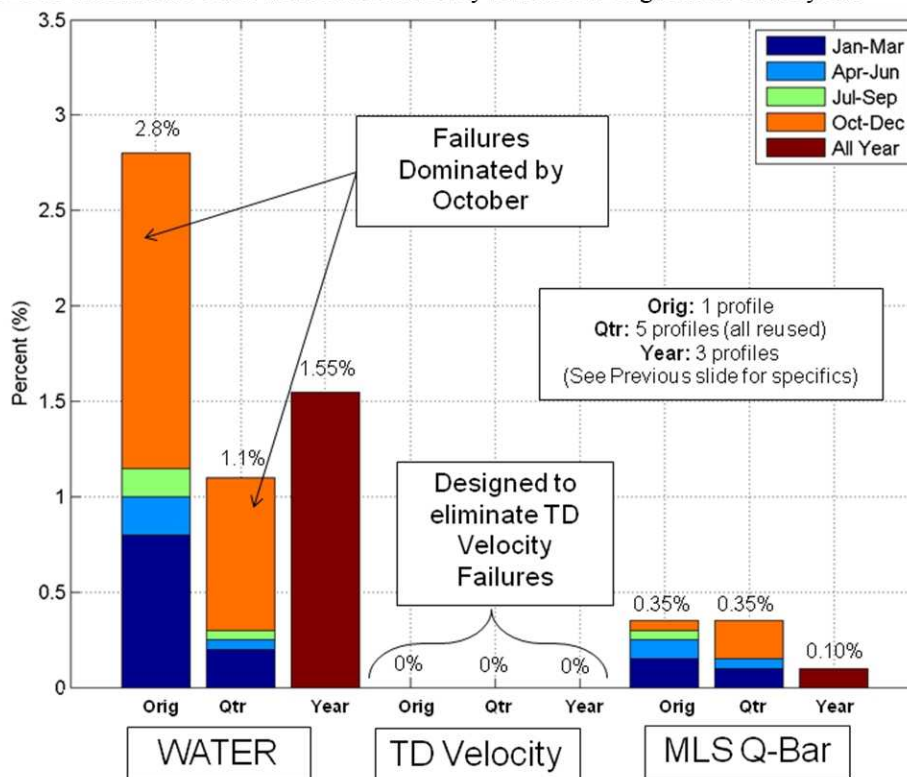


Figure 9. Failure reduction with profile selection based on Table 1

The size of the bar indicates the total number of failures, while the different colors show the breakdown by season. (The year bar has failures in each quarter like the other bars but the breakdown is not shown.) The main observation to draw from this plot is the large decrease in water failures. In general, the number of failures is cut approximately in half with no increases in touchdown velocity failures or q-bar exceedances at main line stretch. The quarterly based profile performs better in water failures but does not aid in the q-bar reduction. Q-bar failures are related to touchdown failures in that lofted trajectories help reduce this metric, as shown in the previous sections. While the quarterly profiles overall decreased the number of water failures more, the yearly profiles have an actual (a therefore more effective) decrease in q-bar failures.

It was of utmost importance that the touchdown failures percentage remains zero due to the desire to maintain or decrease failure levels in categories other than water landing and the general consensus that touchdown velocity exceedances are more undesirable than land landings. If this metric was allowed a small increase (a few tenths of a percentage), the water failures could be reduced even further. But this is not a trade the Orion community is prepared to make. In other words, if all failures were equal, the optimum for minimizing overall number of failures would trade touchdown failures for more water-line failures.

To better understand the effectiveness of the quarterly profile design, the same profiles were selected for quarterly Monte Carlos that each contained 2000 cases with a total yearly count of 8000 cases. The same trends exist, but the water failure percentages are all increased. This is surprising considering almost the same proportions of cases are in each quarter. The increases are not equal across the board: the 4th quarter contained most of the new water line failures. Also the performance gap between quarterly and yearly profiles is narrowed. Finally, the increased risk of selecting less lofted profiles shows up. The percentage of touchdown failures is measurable at 0.08% and 0.01% for quarterly and yearly selections respectively:

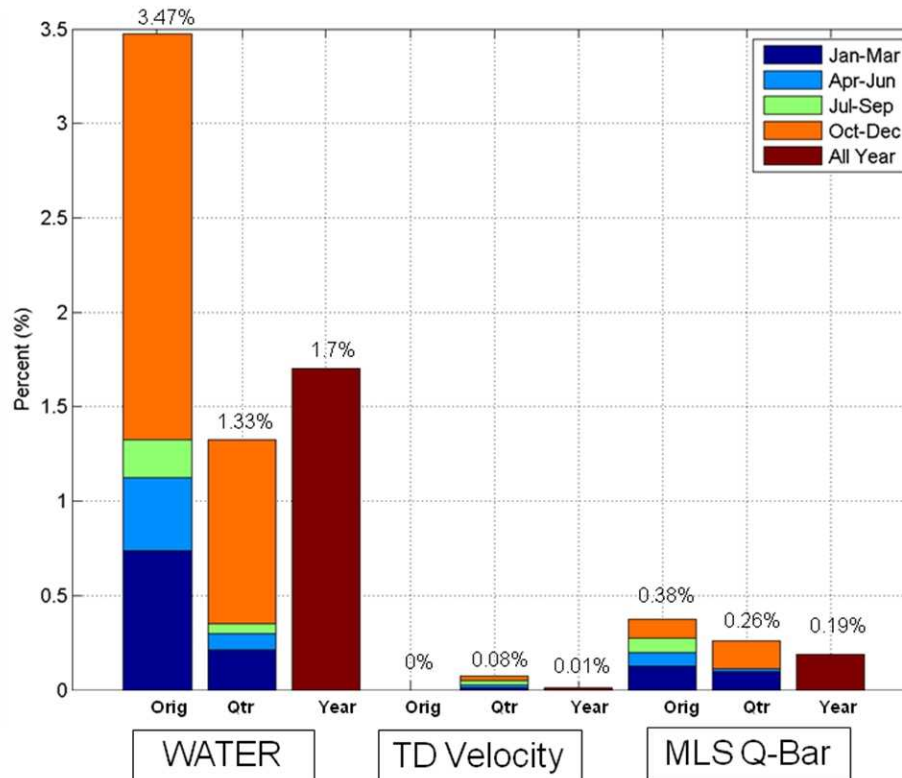


Figure 10. Failure reduction for 8000 case Monte Carlo with profile selection based on Table 1

It is not overly surprising that in the 2000 case Monte Carlo no touchdown failures existed the number of equivalent cases from a 2000 set for the above percentages are 1.6 and .2 respectively.

Other configurations can be tested too. The following plot shows that the ISS 1&2 and Lunar pad mass configurations provide the exact same reductions and percentages, while the Basic configuration (mass is minus manager's reserve) has exceptional performances. However, the number of failures for the Basic with a single profile is also greatly reduced when compared to the other two mass configurations:

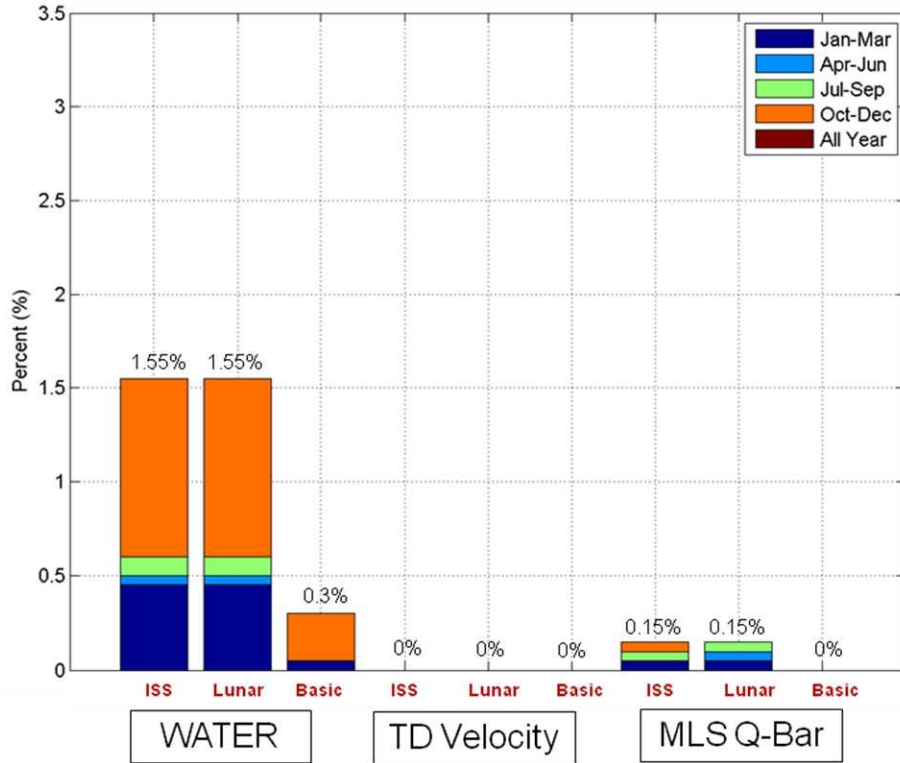


Figure 11. Failure reduction for 8000 case Monte Carlo with profile selection based on Table 1

E. Wind Placard Changes with Profile Selection

In order to determine wind placards based on wind conditions that can be extremely unpredictable and variable, it is necessary to determine what types of winds will cause failures, in this case those that result in land impact. Thus, a placard is based on a set of data that has first been categorized.

The wind categorization developed for this analysis is based on average wind value and the average azimuth direction of a particular wind of the day. Of course winds constantly change direction and magnitude. So while an average wind might give an idea of the general course of a particular wind it doesn't account for gusts or the direction of that particular gust or the altitude that is most problematic. Accounting for gusts or where within the 0 to 4000m altitude band the wind is strongest, does not improve the wind placard categorization significantly. Thus, it should not be too surprising that there is a wide range of azimuths (within a region near the headwind direction) that produce unacceptable water failures. Figure 12 below shows different percent failure levels for given azimuth wedges of 20° ranging from 95% to 100% for the original pitch profile. Figure 13 shows the same percentage levels for the select 3 pitch profiles.

Three of the wedges in Figure 12 always have more than 5% total failures (for that wedge) as shown by the bottom right plot. For the select 3 profiles in Figure 13 this drops to two wedges with total percentages settling at nearly half the original values from an average of 15% to 7%.

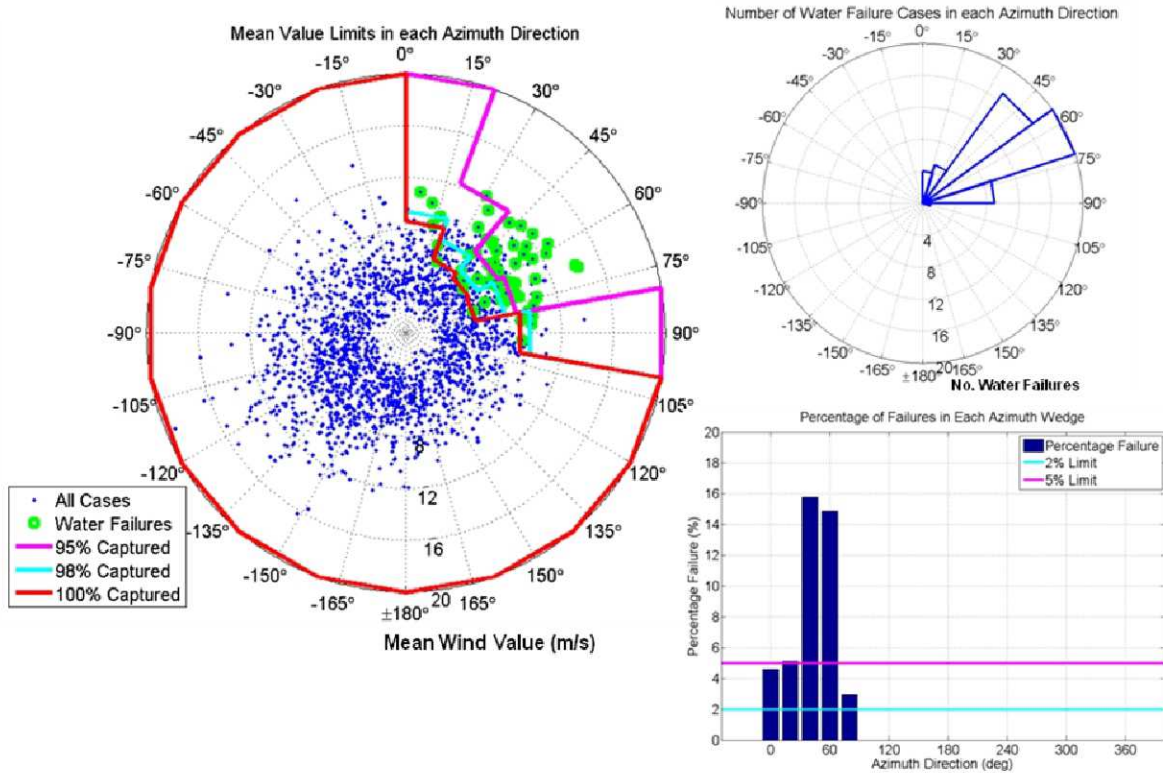


Figure 12. Original Profile water failures; percentages and tallies calculated in 20° intervals

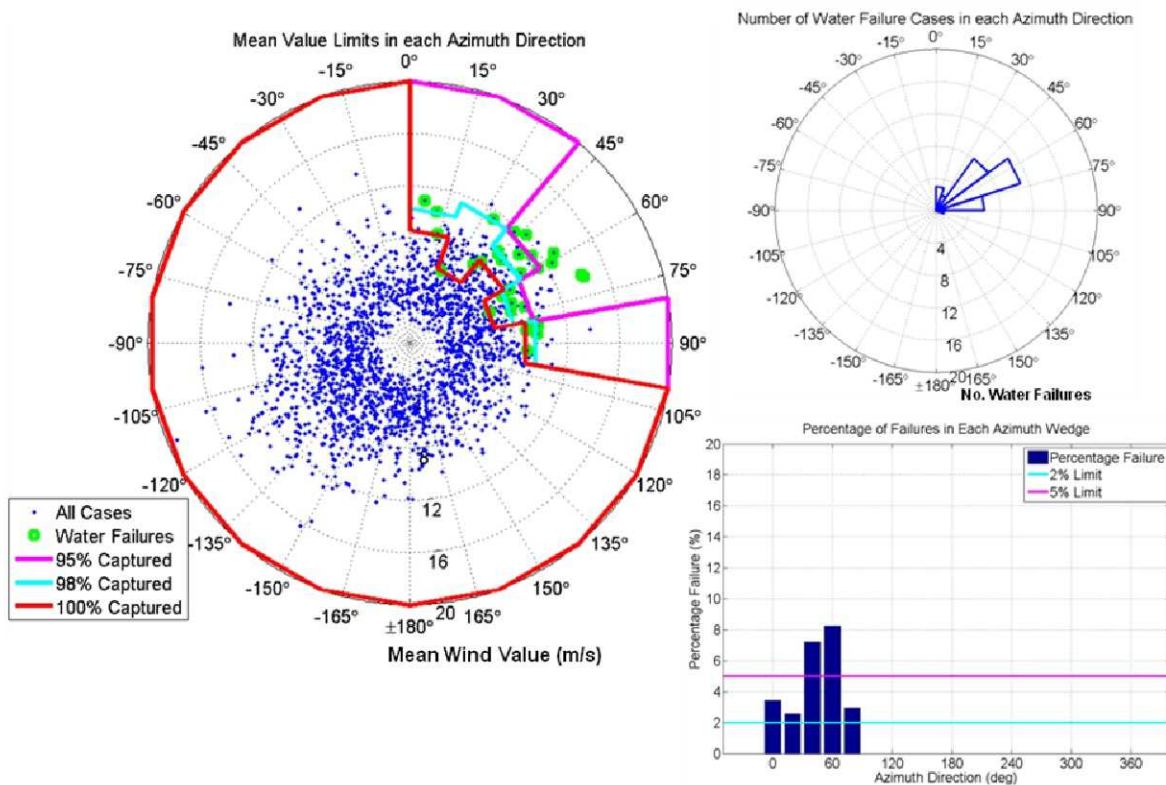


Figure 13. Select 3 Profile water failures; percentages and tallies calculated in 20° intervals

The pad abort cases with both original and select 3 pitch profiles were also run with the Lunar configuration and Basic configurations. The Lunar configuration produced nearly identical results. However, the Basic configuration performs much better. With a lighter CM, a less lofted pitch profile is a viable option in all categories, including the original profile as Table 1 shows and Figure 14 demonstrates below:

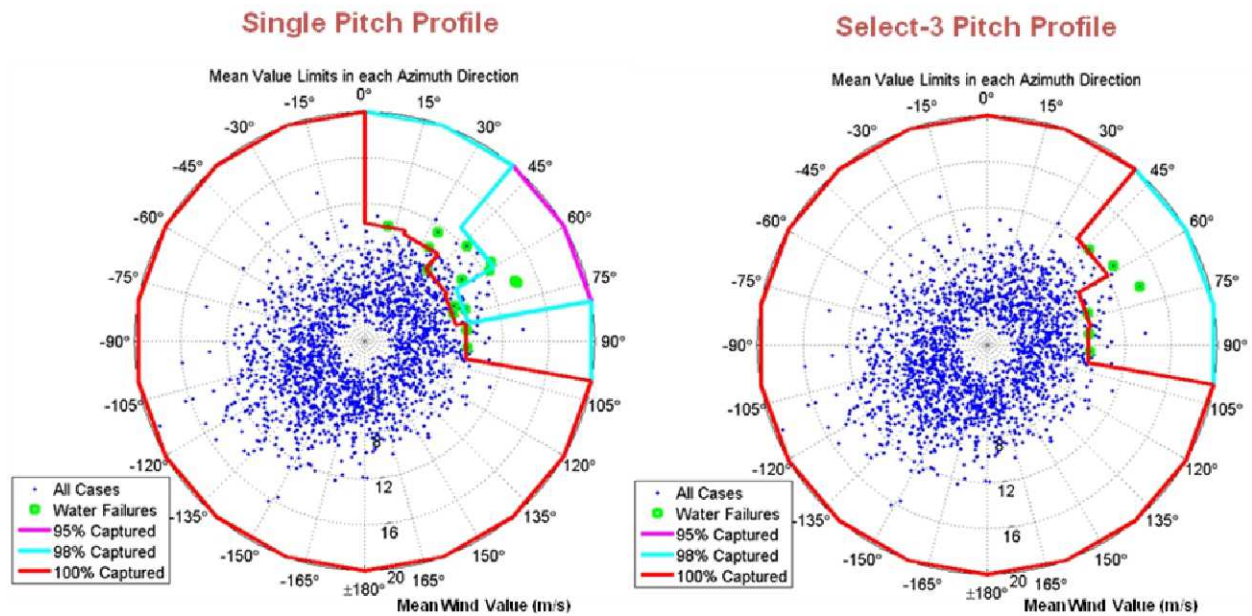


Figure 14. Basic Configuration Original vs. Select 3 Profile water failures

Comparison between the original and select 3 pitch profile approaches show improvement in margins with respect to the percentage of waterline failures in each azimuth direction. However, there is not necessarily a large improvement in launch availability percentage. The availability percentage is calculated by counting the number of cases larger than a minimum constant velocity value applied across the azimuths with waterline violations. In other words, the launch availability is analogous to the number cases that remain after applying a minimum wind placard. In the ISS1&2 and Lunar cases, the launch availability improves from 82.15% to 84.9%. The Basic configuration improves from 93.8% to 97.1%.

F. Drogue and Main Chute Failure Effects

In addition to dispersions, pad aborts must be successful in the case of a single chute failure. Multiple chute failures are not taken into account regardless of the type: drogue, main, or a combination of drogues and mains. The largest concern associated with a chute failure with regards to the performance metrics is an exceedance of the accepted touchdown velocity. The following table records the number of additional or fewer failures for this parameter as well as waterline failures:

Table 3. Chute failure statistics

Failure Metric	Wind	Categorization	All Chutes	1 Drogue Out	1 Main Out
Water Failures	Headwind	Original	2.6%	2.5%	0.7%
		Select Year	1.35%	1%	0.25%
	Tailwind	Original	0	0	0
		Select Year	0	0	0
	Compromise	Original	0.2%	0.2%	0
		Select Year	0.2%	0.2%	0
	Total	Original	2.8%	2.7%	0.7%
		Select Year	1.55%	1.2%	0.25%
TD Velocity Failures	Headwind	Original	0	0	0
		Select Year	0	0	0.1%
	Tailwind	Original	0	0.05%	0.1%
		Select Year	0	0	0
	Compromise	Original	0	0	0
		Select Year	0	0	0
	Total	Original	0	0.05%	0.1%
		Select Year	0	0	0.1%

Chute out conditions actually help the vehicle reach the water, especially when a main chute is assumed failed as shown in the top half of Table 3 for a headwind; the failure percentage drops from 2.6% to 0.7% for the original profile and from 1.35% to 0.25% for the select-3 profiles. With only 2 main chutes, there is less drag and therefore less time to allow a headwind to cause the vehicle to drift back onto land. However, this naturally corresponds to an increase in the number of times the vehicle exceeds the touchdown velocity limit. The second half of Table 3 shows these increases which are smaller for the select-3 approach although both select-3 and the original profile approach have negligible failure increases with a maximum of .1% or 2 out of 2000 Monte Carlo cases.

IV. Conclusions

This analysis has demonstrated the benefits of incorporating an array of profiles based on day-of-launch wind data into the pad abort guidance design. The proposed baseline array size is 3, designed for the entire year instead of by season or by month. In general, selecting from multiple open loop pitch profiles instead of one reduces the number of waterline failures significantly. Specifically selecting from 3 for the configurations examined eliminates approximately half of these failures. Applying this concept, wind placards will likely still be required if better than 95% of the cases in all individual azimuth directions are designed to succeed. Placard design is ongoing and will be determined in concert with agency wide teams including KSC Range, MOD, Orion Project and Constellation. The increased operational complexity and risk has not been fully assessed and should be analyzed in the future. Analysis integrating pitch profile selection with chute architecture and timeline changes has begun and will continue to be worked; this includes re-optimizing the pitch maneuvers along with the necessary architecture changes.

References

- ¹ "Guidance Navigation & Control Data Book," LM CEV-T-078, 2008.